NARROW PULSE MODULATION OF MILLIMETER WAVE TUBES

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Summary

Various techniques for producing narrow pulse ($\leq$ 5 ns) modulation of millimeter wave tubes, such as extended interaction amplifiers, magnetrons, and traveling-wave tubes, are discussed. In order to achieve the narrow pulsewidth, the switch, pulse forming circuitry, as well as the tube interface, must satisfy very stringent requirements. In particular, the switch must operate at kilovolt (kV) levels and must be capable of the following: 1) fast risetime and falltime ($\lesssim$ 1 ns), 2) large peak currents ($\gtrsim$ 50A), and 3) high pulse repetition frequencies ($\approx 2 \times 10^4$ Hz). The switch techniques described include near term approaches using tube technology (shielded thyratron, planar triode), as well as longer term solid-state approaches (avalanche transistor, optically activated switch). A hybrid approach (thyratron in combination with a ferrite sharpener) is also described. Experimental results representative of each technique are presented. Comparisons and the merits and drawbacks of each technique are discussed.

Introduction

In recent years efforts to develop narrow pulse ($\leq$ 5 ns pulsewidth) modulators for millimeter (mm) wave tubes have intensified.[1-3] Such modulators have drawn attention because of their ability to improve resolution in mm wave systems. In order to achieve kV pulses with nanosecond (ns) pulsewidths, high voltage, high speed switches are essential. Of course high speed switches by themselves will not insure narrow pulse operation. The discharge circuit, which includes the switch, pulse storage and forming circuits, as well as the tube interface, must be carefully considered as well. If possible, the discharge circuit should be incorporated into a transmission line so that the pulse may be delivered to the tube load without being slowed down or distorted.

The goals established for narrow pulse modulators are quite stringent: 1) pulsewidths of less than 5 ns, 2) peak voltages of 2-13 kV, with the exact voltage dependent on the tube type, 3) large peak currents (at least 50A for even the lower voltage tubes), and 4) PRF of 20 kilohertz(kHz). Besides the difficult task of achieving these electrical goals, there also exists very stringent specifications with respect to size and weight. Bulky, inefficient modulators are unacceptable.

The purpose of this paper is to examine various switches for their ability to satisfy narrow pulse modulator requirements. The types of switches compared include: thyratrons, planar triodes, avalanche transistors, optically activated switches, and a hybrid switch consisting of a thyratron and a ferrite transmission line. As anticipated, a particular switch may be strong in one area of operation, but weak in another. Experimental results for the various switches are summarized, using loads which are either 50Ω or a simulated tube impedance. In one case, however, we present experimental results with the actual mm wave tube, a 95 gigahertz (GHz) magnetron (EEV 5163). Output RF waveforms from the magnetron were obtained under conditions of narrow pulse modulation.

As mentioned previously, the pulse voltages required by mm wave tubes will vary, depending on tube type. At 95 GHz, for example, extended interaction tubes require about 13 kV for cathode pulsing. Recently these tubes have incorporated a focus electrode which serves as a modulating grid electrode and requires only about 2.5 kV, thus easing the modulation problem considerably. Magnetrons are cathode pulsed and require about 11 kV. Traveling-wave tubes, now under development, will require about 3 kV. One technique now being developed, which promises to reduce modulating voltages considerably, is the bonded grid cathode.[4] Modulation voltages in the 500-1000 volt range are anticipated.

Before describing the various switches it is worthwhile to briefly characterize the equivalent impedance of the tubes. The choice of switch and modulator circuit hinges on the tube impedance and its operating level. By and large the tube may be considered a parallel combination of capacitance and resistance. In most cases, the resistance is nonlinear in as much as the resistive component becomes effective only after a certain voltage threshold (the value depending on tube type) is achieved. Typical values for the resistance vary from 1 kΩ to 20 kΩ, the actual value again dependent on tube type and operating conditions. Tube capacitance is typically 30 picofarads (pF).

Aside from the equivalent circuit representing the modulating electrode, the RF response to the voltage must be taken into account. After threshold, the RF will not completely follow the modulator voltage. In particular, for oscillator tubes (extended interaction oscillator and magnetron) the RF buildup time may cause a delay of several ns in RF output, beyond the point in which full modulator voltage has been achieved. This effect will be reported on elsewhere for the case of the extended interaction oscillator.[5]

So far as high speed narrow pulse operation is concerned, the tube load will be considered a capacitor. Thus, in order to achieve fast risetimes, large peak currents are required to rapidly charge up the capacitance, and low impedance modulator circuits are necessary. External matching circuitry, including a terminating resistance equal to the characteristic impedance of the modulator circuit, may be included to minimize reflections and ringing at the load. If necessary, an additional switch may be used to rapidly "pull-down" the voltage on the load capacitance, thus insuring a fast falltime. In terms of circuit simplicity, the matching circuit approach, without the extra switch, is preferable.

Discussion

Shielded Thyratron

A pulser employing a shielded tetrode thyratron was able to produce extremely narrow RF waveforms ($\lesssim$ 5 ns) in a 95 GHz magnetron (EEV 5163). The circuit (Figure 1) was a pedestal type. By this, it is meant that a bias pulse or "pedestal" ($\approx$ 50 ns wide) was first applied to the magnetron, using a Blumlein circuit. A much narrower "sliver" pulse ($\approx$ 5 ns wide)

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14. ABSTRACT

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which is produced by the shielded thyratron, was superimposed onto the bias pulse so that the total voltage fell within the operating voltage of the magnetron. The coupling capacitor accomplishes the superposition while a "pull-down" resistor rapidly reduces the sliver voltage without the necessity for a separate switch. The pedestal was typically 8.7 kV, slightly below the threshold of the magnetron. The sliver was about 2 kV. Figure 2a shows a typical RF waveform with a pulsewidth of $\approx$ 4 ns and a peak output of approximately 1 kilowatt (kW). By reducing the pedestal voltage approximately 1000 volts, it was possible to achieve pulsewidths as narrow as 2 ns, thus approaching the risetime capability ($\approx$ 1 ns) of the instrumentation. The pulse narrowing is a result of the fact that for the same sliver voltage, but at lower pedestal voltage, the operating threshold occurs closer to the top of the sliver pulse, effectively reducing the pulsewidth of the RF pulse. Of course one sacrifices RF amplitude at the lower pedestal voltage (peak power was about half that at full pedestal). The original power level must then be restored by increasing the pulse amplitude of the sliver, which is a more difficult task. Figure 2b shows a somewhat wider RF waveform during a 30 second exposure with the magnetron operating at a pulse repetition frequency (PRF) of 120 hertz (Hz). Amplitude jitter is approximately 20 percent and time jitter is approximately 2 ns. A significant portion of the jitter can probably be eliminated by improved circuit filtering. It is also important for the pedestal to have a flat top so that changes in delay of sliver relative to pedestal will not be manifested by amplitude variations.

Avalanche Transistor

In recent years Hughes (Fullterton, CA) has made significant progress on ns pulsers utilizing avalanche transistors.[2] A group of ten transistors are arranged in a Marx circuit, i.e., the transistors are charged in parallel and are then discharged in series (Figure 3). One kV pulses, with pulsewidths of 2 ns and risetimes less than 0.4 ns, have been delivered into a 50Ω load. At present, a separate Marx circuit is utilized to "turn off" the pulse. Pulsewidth is determined by the delay time between the "turn-on" and "turn-off" trigger pulses. The same transistors also are used to isolate the "turn-on" and "turn-off" circuits from one another, so that one circuit does not inadvertently trigger the other. Effort is being made to incorporate the transistors into a low impedance microstrip line, thus eliminating unwanted parasitics. Peak current capability for narrow pulse operation has yet to be determined (presently the transistors are operated at 20A peak). If necessary, some transistor modifications may be introduced to improve high peak current operation. At present high speed step-up transformers (2:1 and 3:1) are being developed. The transformers will be combined with the 1 kV avalanche module to produce pulse amplitudes of 2-3 kV. The transformers are transmission line types [6] and appear to be capable of risetimes less than 200 picoseconds (ps). Low impedance transmission lines ($\approx$ 10Ω) must be employed in order to achieve the desired current levels.

Planar Triode

Another tube capable of producing kV, ns pulses (besides the thyratron) is the planar triode. Many planar triodes are available which operate into the microwave region, implying a ns switching time. Unlike the thyratron, the triode recovers very rapidly (the triode is a vacuum device whereas the thyratron is gas filled) so that a PRF as high as 1 megahertz (MHz) is possible. The main question concerning triodes has been the peak current capability. However, for ns pulses, peak currents in the 25-50A range have been observed for 2cm^2 cathodes, and this is sufficient to produce ns pulsewidths in several mm wave tubes of interest. Triodes have also been successfully operated in parallel to achieve greater current levels.

In order to maintain the fast risetime response, the grid drive must be both fast and of sufficient current level to quickly charge up the triode grid capacitance. Avalanche transistors in combination with transmission line transformers may be used to drive the grid. For higher voltage triodes, a smaller triode may be used as a first stage to drive the grid. Grounded grid techniques should be employed to eliminate Miller capacitance effects. Figure 4 shows a $\approx$ 2.5 ns wide 5 kV pulse delivered into a 50Ω load.[7] The circuit employs three parallel Y690 Eimac triodes.

Since the triode is a true amplifier, flat top pulses with both fast risetimes and falltimes are easier to obtain (provided necessary current levels are attainable). Matching circuits, which incorporates the load capacitance, may be effective in preserving the fast pulse characteristics at the load without the necessity of an additional pull-down triode.

Ferrite Pulse Sharpener

The ferrite pulse sharpener consists of a long coaxial transmission line (typically 100 centimeters (cm) long) in which the space between conductors is filled with ferrite material.[3] A slow risetime pulse presented at the input will emerge from the ferrite line with a sharpened risetime because of the nonlinear permeability of the ferrite. The sharpener has the advantage of allowing one to obtain fast risetimes by combining this device with an available slow risetime circuit. For example, it may be inconvenient to minimize risetime in a circuit, caused by a slow switch or slow circuity. As another example, one may wish to use a low pressure thyratron (which has a long resistive fall time) in order to maintain maximum voltage holdoff. At present, the ferrite sharpener has produced 5 kV pulses with 2 ns risetimes, with a 10 times compression ratio, delivered into 50Ω .

A disadvantage of this type of device is that, in order to obtain narrow pulsewidths, two ferrite lines are required. As shown in Figure 5, the circuit basically involves pulse differentiation. At the input the lines are connected in parallel. At the output the lines are connected in phase opposition to one another. Pulsewidth is determined by the amount of pulse delay in one line with respect to the other line. The relative delay is controlled by bias currents in their respective lines. Using the dual ferrite line, 4 kV pulses with pulsewidths of 5 ns were delivered into a 50Ω load. Very fine control of the bias currents must be exerted in order to prevent the appearance of secondary pulses, caused by incomplete pulse cancellation.

A lumped circuit version of the ferrite sharpener is also possible, provided the risetime limitation is caused solely by resistive fall time in the thyratron, and not by inductance effects.[8] By placing several ferrite toroids in the discharge

circuit, the current is delayed, giving time for the thyratron plasma to build up. When the ferrite saturates (after several ns) the anode potential has for the most part fallen. Care must be taken not to add too many toroids since this will add residual air core inductance and the risetime will then worsen. The technique appears to work best for initial risetimes less than 10 ns.

Optically Activated Switch

A promising long term approach for ns pulsers makes use of the phenomenon observed when a semiconductor material is illuminated with concentrated light from a laser. The light energy produces secondary electron and hole carriers in a region ≈ 100 microns thick. The introduction of carriers causes the resistivity to drop suddenly from its initial high state to a much lower value. Figure 6 illustrates the concept using a gallium arsenide (G_aA_s) diode laser as the light source. The conductor of a transmission line (either microstrip or coaxial) is mounted on the semiconductor material. A gap (typically 1 mm wide) in the conductor exposes the semiconductor, which is then illuminated by the laser, producing carriers and causing the device to switch. The waveform shown was obtained with a 40 watt G_aA_s laser using high resistivity silicon ($\approx 10^4 \Omega$-cm) for the semiconductor. The relatively large falltime is caused by positive mismatch arising from the residual resistance in the gap ($\approx 200\Omega$). Increasing the degree of ionization will reduce gap resistance as well as the risetime.

One of the problems with this device is that, for good ionization, large peak powers (> 50 W) from the laser are required. In order to minimize the amount of laser power the avalanche mode of operation will be investigated. The laser serves to "tickle" the semiconductor into avalanche. Both silicon and G_aA_s are being investigated. Slightly doped G_aA_s appears to have certain advantages because of its lower recombination time (≈ 100 ns) compared to silicon (whose recombination time is several microseconds). This means megahertz PRF will not be limited by recombination in G_aA_s.

Comparison of Various Switching Techniques

Of the switches described here, there appears to be two near term approaches for producing ns modulators. These are the shielded thyratron and the planar triode. The thyratron offers more than sufficient current and its switching speed is moderately fast (≈ 2 ns). When used in a shielded design it can produce 4 ns wide pulses in the 2-3 kV range, suitable for the gridded type mm wave tubes. It is also suitable as a sliver pulser such as that used for the magnetron. If the particular mm wave tube exhibits sharp threshold characteristics, and the tube is biased well below threshold, the RF pulse may actually be narrower than the modulation pulse. As regards the planar triode, its switching speed is quite fast (≈ 1 ns) and is capable of supplying pulse voltages up to 13 kV. It is also capable of very high PRF (≈ 1 MHz), should such requirements arise. Heater requirements for the triode also are generally less than that of the thyratron. The main drawback is that peak current may be marginal (25 to 50A for each triode). Paralleling of such triodes may provide an answer, although this adds to complexity and size.

Among the remaining approaches, the avalanche transistor appears to have good long term potential. Its inherent switching speed is probably less than 100 ps. The present voltage output of approximately 1 kV will be boosted to the 2-3 kV range by high speed transmission line transformers, making the output compatible with gridded type mm wave tubes. Parallel operation of transistors, or possibly further development on the transistor, may be necessary in order to increase the peak current capability.

The dual ferrite transmission line sharpener can generate 4 kV pulses into a 50Ω load with a 5 ns pulsewidth. Since the input switch is typically a thyratron, the device does not suffer from current limitations. The main advantage is that one can start off with an available slow risetime circuit and add the sharpener circuit to obtain narrow pulses. The main disadvantages are size, complexity, and the fine tuning needed to suppress secondary pulses.

The optically activated switch is a long range approach for producing ns pulses at very high PRF. Much work remains to be done, however, to increase the carrier density in the semiconductor with a minimum of laser power. In addition, peak voltage and current levels must be boosted.

Conclusions

Various pulsers suitable for ns modulation of mm wave tubes have been investigated. At present the near term approaches rely on tube operation, either a thyratron or a planar triode. The longer term approaches are solid-state. High speed solid-state devices are presently limited in both peak voltage and current. Naturally, the solid-state approaches will find application sooner if lower modulation voltages for mm wave tubes are realized. When this happens, other solid-state contenders, not considered in this paper, such as high speed SCR or MOSFET devices, may also become useful.

References

1. M. Weiner, W. Beattie, "Generation of Nanosecond Pulses with a Thyratron Switch," Record of Fourteenth Pulse Power Modulator Symposium, pp. 179-182, June 1980

2. J. Stover, N. Komatsu, A. Nieto, "Nanosecond Pulsers for Millimeter Wave Tubes," Third Interim Report, Contract DAAB07-78-C-2991, February 1980

3. M. Weiner, "Pulse Sharpening in Ferrite Transmission Lines," Digest of Second IEEE International Pulsed Power Conference, pp. 91-95, June 1979.

4. G. V. Miram and E. L. Lien, "Electron Gun With Bonded Nonintercepting Control Grid," IEDM Technical Digest, 1976

5. D. Ladd, Georgia Institute of Technology, to be published

6. R. Matick, "Transmission Line Pulse Transformers - Theory and Applications," Proc. of IEEE, Vol. 56, pp. 47-62, January 1968

7. S. Davis, Pico Second Enterprises, Private Communication.

8. S. Schneider, "Magnetic Assist for High Power Switching," Final Report, Contract N60921-79-D-A206, December 1980

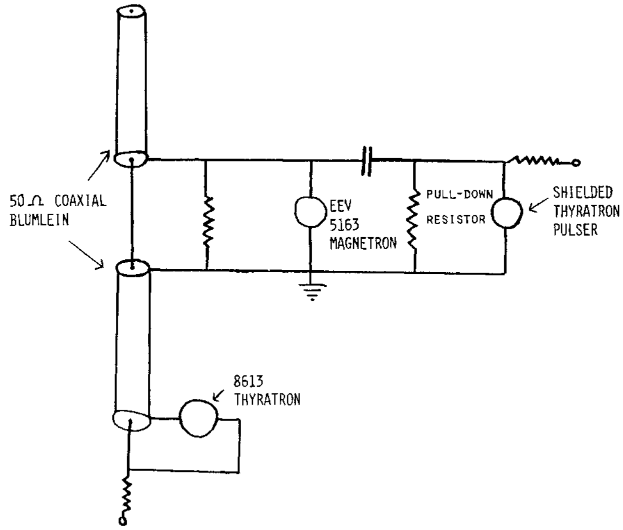


Figure 1. Pedestal pulser circuit employing a shielded thyratron for the sliver pulse.

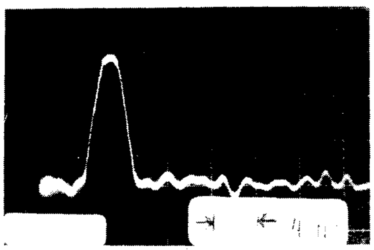


Figure 2a. Output RF waveform of EEV M5163 magnetron. A single waveform is captured with the storage scope.

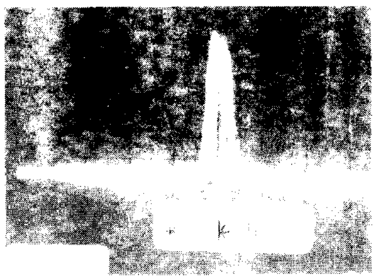


Figure 2b. Output RF waveform of EEV M5163 magnetron at PRF of 120 Hz and 30 second exposure.

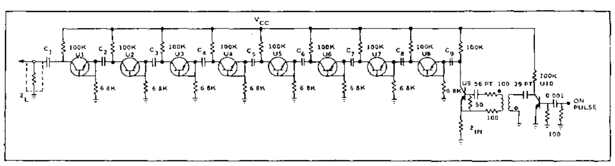


Figure 3. Avalanche transistor pulse circuit. The transistors U_N (N a positive integer) are arranged in a Marx circuit. Capacitors C_N are charged to voltage V_{cc}. Z_L is the resistive load.

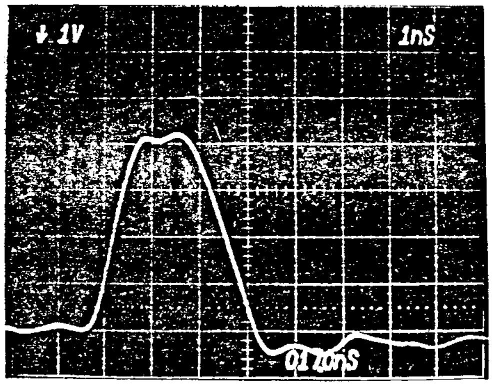


Figure 4. Five kilovolt pulse delivered into 50 Ω load, using Y690 Eimac triodes (three in parallel).

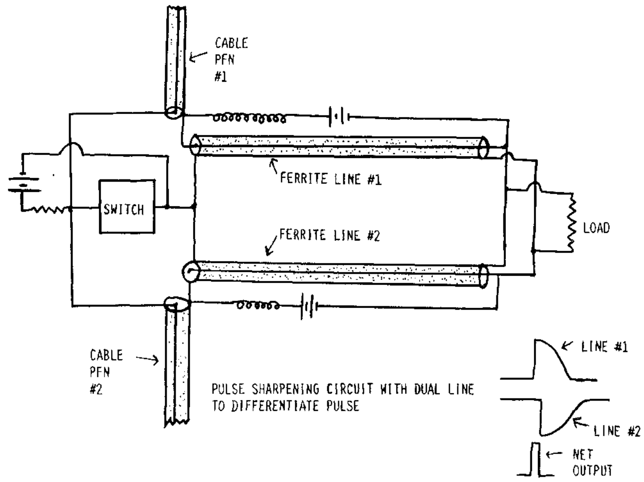
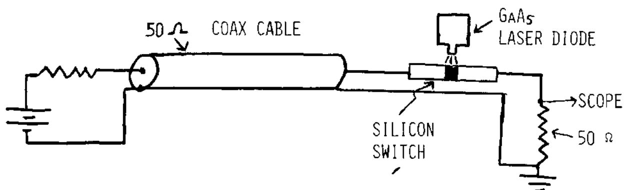
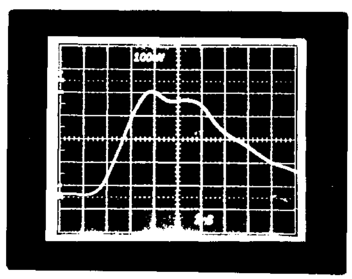


Figure 5. Ferrite pulse sharpening circuit. Line #1 sharpens the risetime while Line #2 sharpens the falltime.



OPTICALLY ACTIVATED SILICON SWITCH CIRCUIT



WAVEFORM OF PULSE VOLTAGE ON LOAD. HORIZ: 2 NS/CM

Figure 6. Optically activated switch circuit Waveform is a 40 volt pulse delivered into 50 Ω load.